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Shear Characterisation of Woven Carbon/Epoxy Composite Under Various Adverse Environments

P. K. Dash and D. Singh

Department of Aeronautical Engineering, Hindustan University, OMR, Padur, Chennai, TN, India

ABSTRACT: In this article, an investigation into the shear properties of bi-directional carbon fibre reinforced composite has been carried out by 'rail-shear' test method (D4255). The specimens were tested under various adverse environmental conditions after subjecting them to different durations of exposure. A comparison between time-dependent degradation of the shear properties of the material with respect to virgin shear properties is made, and the results have been analysed with emphasis on material weight gain or loss under those adverse environments.

KEY WORDS: *adverse environments, rail-shear test, shear modulus, shear strength, woven carbon/epoxy composite*

NOMENCLATURE

A	Area
b	Length
C	Constant
e	Elongation
G	Shear Modulus
h	thickness
M	Moisture content in form of weight
n	Total number of points
γ	Shear strain
ϵ	Tensile strain
P	Load
S	Standard deviation
τ	Shear stress
ν	Poison's ratio

SUB SCRIPTS

f	Final
i	Number of tests
x	X- Co-ordinate
y	Y- Co-ordinate

Introduction

Strength and stiffness of composite materials are two favourable properties that are used to full extent in various structural applications under different kinds of loadings. One of the essential requirements for this extensive usage is the need to understand the behaviour of these materials under different loading and environmental conditions. Any uncertainty in this regard will result in improper utilisation of the material properties, and will result in smaller or larger margin of safety in design. Now, with loadings and environments to which these composites are subjected to are so varied and complex, a complete understanding of the material response over the entire range of loads and environments is necessary. This will help considerably, if advanced analysis and design procedures are employed for efficient material utilisation. Furthermore, the distinguishing feature of unidirectional composites is that they have high strength and high modulus in the direction of the fibre axis. This is more advantageous where the state of stress can be accurately determined and laminates can be fabricated with fibres, having strength that can match the design needs. However, in applications where the state of stress may not be predictable or where the stresses are approximately equal in all major directions of loading, there is a need to develop composites that have approximately equal strength in all directions. In this context, the bi-directional carbon fibre reinforced composite has attracted the attention of researchers and scientists to fulfil the analysis and design requirements under multi-directional loadings and also enable selection of the material. Even though number of test results are available for such composites, specific environmental and load conditions like saline water exposure or shear loads call for more elaborate needs and this study relates to such cases.

The specific requirements for load and environment are different from the commonly used shear fixtures and loadings in open air. For example, fixtures that are used for shear loadings are satisfactory for metallic structure and when they are used with

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brittle composite materials, unanticipated failure modes and low-failure loads have resulted. Further, a matrix-dominated material has characteristics that depend on environments, and property tests are required to assess environmental degradation of polymer matrix composites. So, it was decided to use the in-plane shear test as it is ideal for such studies, both from loading and material degradation points of view. But to reflect the influence of different parameters affecting the response, sizeable number of tests is necessary so that statistical interpretation of the valid data is possible in degradation studies of materials. Moreover, an uncomplicated and rapidly executable test is desirable to ensure that material characterisation is possible, resulting in easier application of these advanced materials in design, with reasonable safety margin. With this objective in focus, a study on in-plane shear test techniques, which can be carried out on laminate flat plates, was made and recent literature studies [1–21] have endeavoured to present comparisons of the popular shear testing and analysis methods.

In this article, an experimental investigation was performed on selected rail-shear specimens (as shown in Figures 1 and 2) to assess the effects of specimen geometry, loading and environmental influences, on in-plane shear modulus and ultimate shear strength of bi-directional carbon/epoxy composites. The parameters were chosen as tensile load induction path, effect of rail configuration, different environmental effects like water, saline water, acidic water, organic fuel, low temperature (ice) and hot air (60 °C). Further, with different duration of prior exposure, role of weight change under such conditions, stress–strain characteristics and tangent modulus were studied based on the data obtained from this test programme and these are presented.

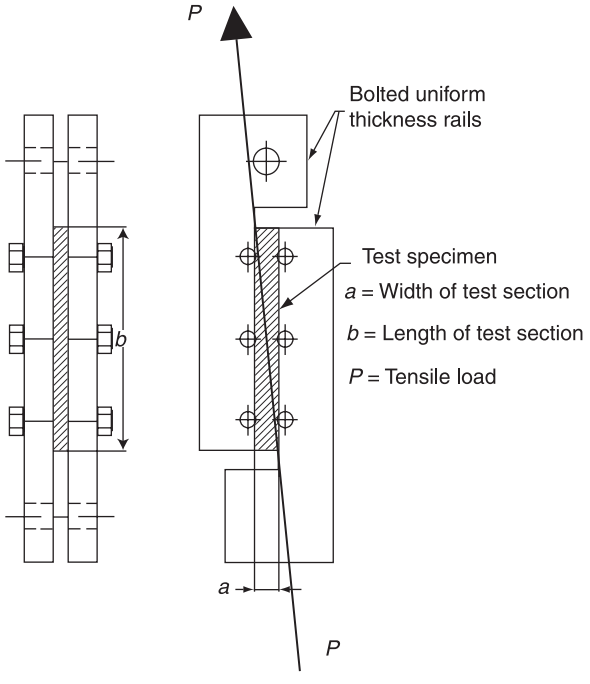

Figure 1: The rail shear configuration

Different Shear Test Methods

A large number of testing procedures have been introduced for measuring in-plane shear properties of materials. The most popular and widely accepted of these tests include the rail-shear test, the ± 45° shear test and the 'off-axis' shear test. A modified 'lap- shear test' can also be used to measure the out-of-plane shear modulus for certain materials. Each of these experiments has its own advantages and disadvantages. Here, these experiments are briefly reviewed.

Rail-shear test (D4255)

The rail-shear test was suggested as a procedure for measuring the in-plane shear properties of laminated composite materials [3, 12]. Shear stress is applied to plate specimens by gripping large areas of the laminate surface along each side (Figure 2). The long, narrow central region is assumed to be in pure, statically determinate shear according to the relationship

$$\tau = \frac{P}{A} \tag{1}$$

where A is the area equal to plate thickness multiplied by the length of the specimen, P is the applied load, and τ is shear stress. The test-zone length to width aspect ratio should be at least 10 to achieve nearly uniform shear in the test section. Unfortu-

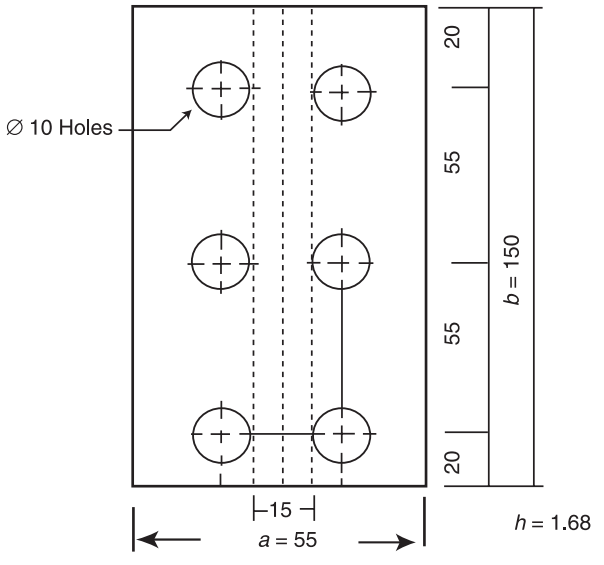

Figure 2: Dimensions of shear specimen (all dimensions are in millimeter)

nately, increase in length has a direct effect on bearing capability of a specimen and consequently, a long gripping area is needed. Therefore, specimens with large aspect ratio (>>10) are required to accomplish this type of load introduction.

$(\pm 45°)_S$ shear test (D3518)

The ± 45° tension test for shear properties is intended to provide the shear stress–strain response of a laminate loaded in uni-axial tension (or compression). Half of the shear stress in the tensile coupon is the tensile stress, and the other half is the intralaminar shear. Interlaminar shear is usually identified as G_{12}, where subscript 1 refers to the fibre direction within the lamina, and 2 refers to the orthogonal direction in the plane of ply. This is a special case of what is generally referred to as 'in-plane' shear, or G_{xy}, where x and y do not necessarily correspond to the fibre directions. So, shear strain can be written as:

$$\gamma_{12} = (1 + v_{xy})\, \varepsilon_{xy} \quad (2)$$

where, γ is shear strain, υ is Poison's ratio, ϵ is tensile strain, and x and y are directional parameters. Thus, by monitoring load and the two principal normal strains, it is possible to approximate the complete shear response of a lamina. However, a combined stress state actually exists in the specimen and the planes of principal shear are subjected to non-zero normal stress. The uncertain effect of the test procedure results in dissimilar values of failure stress in compression and tension loading. So, the failure stress can also be obtained by loading specimens in compression instead of in tension, which result a substantially different values of mean failure stress.

Although the intralaminar shear modulus is the required input parameter for calculations based on theory of laminates, the in-plane shear strength and compliance of mixed ply laminates often must be known. The $(\pm 45^0)_S$- shear test only provides interlaminar shear stiffness properties.

Off–axis test

It is well known that a fibre-reinforced material, which is uniaxially loaded in a direction different from that of the fibres, will be subjected to in-plane shear forces because of the non-vanishing shear-coupling terms of the constitutive relationships. If the angle between the loading and fibre direction is about 10°, then the intralaminar shear stress component will be large enough and closer to its limit value with respect to the longitudinal or transverse stresses [10].

Modified lap-shear test

The 'modified lap-shear' test is a hybrid form resulting from combination of the rail-shear test method with the lap-joint test. A unidirectional laminate is bonded between two metal bars, with its fibres oriented parallel to these 'rails', and is then loaded similarly to the rail-shear test. A laminate failure cannot be achieved with this technique because the epoxy bonding of the specimen to the rails will not be as strong as the reinforced matrix resin. However, if the laminate is reasonably thick, on the order of 2 or 3 mm, shear modulus can be measured by placing 1 mm gage length strain gauges oriented to sense the normal strains at the laminate mid-plane along the sides of the specimen. It can be shown that if the material is transversely isotropic (a unidirectional laminate), then the out-of-plane shear stiffness, G_{13}, approximates the intralaminar shear modulus, G_{12} [1].

Material and Test Details

This investigation has been carried out on carbon fibre reinforced composites manufactured by IPCL, Boroda (India) with trade name INDCARF – 30. The fibres are plain weave with 13–15 ends per inch in both wrap and weft direction. The properties of weaved carbon fibre fabric are mentioned in Table 1.

The epoxy resin used was Araldite LY- 5052, hardened by Hardener HY- 5052 (products of Ciba-Geigy India Ltd) with 100:38. The composite plates were fabricated in the laboratory by a vacuum bag technique and cured at room temperature for 24 h and post- cured at 100 °C for 2 h. The laminates made with eight layers of fabric have a nominal thickness of

Table 1: The Properties of Bi-directional weaved carbon fibre fabric

Weight/sq. metre of the fabric	200 gms
Thickness	0.2 mm
Fibre count	3 K carbon
Yarn denier	
Wrap	54
Weft	52
Weave	Plain weave

Table 2: Mechanical properties of bi-directional carbon/epoxy composite

Mechanical properties	Tensile s trength (MPa)	Young's modulus (GPa)	Flexure strength (MPa)	Flexure modulus (Gpa)
CFRC	585.32	37.069	483.23	30.064

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1.68 mm corresponding to a fibre volume fraction of 55% (±1). The basic properties of the fabricated carbon/epoxy material are presented in Table 2.

The specimens used for rail-shear tests were rectangular plates with dimensions 150 mm × 70 mm as shown in Figure 2. ASTM D 4255 was the test method adopted to conduct the rail-shear test. Prior to the rail-shear tests, the specimens were preconditioned in various environments. The environments selected for experiments were distilled water, saline water (water with 10% $NaCl_2$), acid-water (H_2SO_4 acid of strength N/100), organic fuel (Kerosene), low temperature (ice) and high temperature (hot air of 60 °C). The exposure duration was 100, 200, 300, 400, 500 and 600 h. The influence of environments has been estimated in the form of weight gain/loss of the exposed specimens. The weight loss/gain was calculated as follows:

$$\%\ \text{Wt. gain/loss} = \frac{M_f - M_i}{M_i} \times 100 \quad (3)$$

where M_f is the final weight after environmental conditioning and M_i is the initial weight of the specimen just after fabrication. A minimum of five specimens were exposed to the selected environment for preconditioning and test. In addition to environmentally exposed specimens, tests on the in-plane shear strength of virgin specimens (without environmental exposure) were also carried out for studying the influence of various environmental effects. Basic mechanical properties including tensile strength, tensile modulus, flexure strength and flexure modulus were obtained experimentally and are shown in Table 2.

Rail-Shear Test

The rail-shear specimen with typical dimension of 150 mm × 70 mm × 1.68 mm as shown in Figure 1 is used for experimental determination of shear strength and shear modulus by the rail-shear test method. The fixture introduces tensile load on the specimen's diagonal axis and along the rails, which is of uniform cross-sectional area and bolted to the test material. The specimen has 'over-sized' bolt holes for inducting the loads through clamping action to the test section instead of bolt bearing forces. To prevent overall slippage between the rails and test material, a torque of 61 N-m was applied to each of the six bolts. The rails were fabricated from stainless steel. Two numbers of 0°, 45°, 90°, three element, stacked rosette strain gauges were mounted to each side of the specimen in the centre of the test section. The load was applied to the specimen at a crosshead motion rate 1.27 mm per minute. A digital strain indicator was used to record strain data at specified load intervals. A minimum of five specimens was tested for each set of observations.

The mean value of shear strength obtained from the experiments is presented in Table 3 for the different durations of environmental exposure. The tangent modulus was obtained from the shear stress–strain curves and calculated by taking the first derivative of the polynomial equation for each series of tests. Shear stress–strain curves and shear tangent modulus values are presented in Figure 4 and Table 4 respectively.

Analysis of Experimental Results

The results obtained from the experimental data, being statistical, a regression analysis was performed using polynomial approximations. If failure takes place with out-of-plane buckling or from stress associated with rail bolts, then that presents apparent shear strength.

The shear strength can be calculated using the following equation:

Table 3: Ultimate shear strength (τ) of bi-directional carbon/epoxy composite after different duration of exposure in various environments

Environments → Duration of Exposure (Hrs) ↓	Water MPa	Saline water MPa	Acidic water MPa	Organic fuel MPa	Low temp. (Ice) MPa	High temp. (hot air of 60 °C) MPa
0	49.5106	49.5106	49.5106	49.5106	49.5106	49.5106
100	48.2333	48.4402	47.0022	48.5303	46.1736	48.7193
200	46.5766	47.1236	44.6699	47.2899	43.4359	47.3297
300	44.3338	44.6766	42.2097	45.0418	40.6998	45.3868
400	41.2610	41.8315	39.1846	42.3153	37.7077	43.1016
500	37.8306	38.6220	35.9916	39.5512	33.8766	41.0614
600	34.3636	35.8818	32.7712	36.6012	29.8006	39.5545

Average data of five observations.

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Table 4: In-plane shear modulus (G) of bi-directional carbon/epoxy composite after different duration of various environmental exposure

Environments → Duration of Exposure(Hrs)↓	Water GPa	Saline water GPa	Acidic water GPa	Organic fuel GPa	Low temp. (Ice) GPa	High temp. (hot air of 60 °C) GPa
0	7.030	7.030	7.030	7.030	7.030	7.030
100	7.217	7.229	7.069	7.115	7.335	7.371
200	7.381	7.412	7.102	7.196	7.491	7.682
300	7.476	7.601	7.129	7.285	7.587	8.005
400	7.601	7.790	7.165	7.374	7.655	8.218
500	7.668	7.876	7.213	7.438	7.742	8.537
600	7.726	7.987	7.279	7.495	7.796	8.857

Average data of five observations.

$$\tau = \frac{P}{bh} \tag{4}$$

and shear modulus can be calculated using the equation:

$$G = \frac{\Delta P}{\Delta e(Zbh)} = \frac{\Delta P}{\Delta e}(Zbh)^{-1} \tag{5}$$

For the +45° or −45° strain gauge, G is the shear modulus, τ is the ultimate shear strength, P is the maximum tensile load on rails, b is the total length, and h is the thickness. Here, $\frac{\Delta P}{\Delta e}$ is the slope of the plot of load vs. elongation, which is a function of deformation within the linear portion of the curve.

For each series of tests, the mean value, standard deviation and coefficient of variation can be calculated as follows:

Mean value

$$\bar{x} = \frac{\sum_{i=1}^{N} X_i}{N} \tag{6}$$

Standard deviation

$$S = \frac{\sqrt{\sum_{i=1}^{N} \left((X_i - \bar{x}\right)^2}}{N-1} \tag{7}$$

Coefficient of variation

$$N = \frac{S}{\bar{x}} \times 100 \tag{8}$$

where X_i is the test value of the 'i' test and N is the number of samples.

For obtaining the stress–strain and modulus, polynomial approximations are used and, the first derivative of the polynomial equation for each series of replicate tests can be expressed as:

$$G_{xy} = \frac{d\tau_{xy}}{d\gamma_{xy}} \tag{9}$$

Second order polynomial equation relating shear stress and shear strain is taken as

$$\tau_{xy} = C_0 + C_1\gamma_{xy} + C_2\,\gamma_{xy}^2 \tag{10}$$

and third order polynomial equation relating shear stress and shear strain will be:

$$\tau_{xy} = C_0 + C_1\gamma_{xy} + C_2\gamma_{xy}^2 + C_3\gamma_{xy}^3 \tag{11}$$

The coefficients of the third-order equation are obtained by solving the following matrix equations:

$$\begin{bmatrix} \sum \tau_i \\ \sum \gamma_i\tau_i \\ \sum \gamma_i^2\tau_i \\ \sum \gamma_i^3\tau_i \end{bmatrix} = \begin{bmatrix} n & \sum\gamma_i & \sum{\gamma_i}^2 & \sum{\gamma_i}^3 \\ \sum\gamma_i & \sum{\gamma_i}^2 & \sum{\gamma_i}^3 & \sum{\gamma_i}^4 \\ \sum{\gamma_i}^2 & \sum{\gamma_i}^3 & \sum{\gamma_i}^4 & \sum{\gamma_i}^5 \\ \sum{\gamma_i}^3 & \sum{\gamma_i}^4 & \sum{\gamma_i}^5 & \sum{\gamma_i}^6 \end{bmatrix} \begin{bmatrix} C_0 \\ C_1 \\ C_2 \\ C_3 \end{bmatrix} \tag{12}$$

where, $\tau_{xy} = \tau$, $\gamma_{xy} = \gamma$, and n is the total number of points for series of replicate tests and $\sum$ implies summation for $i = 1$ to $i = n$. Similarly, coefficients of the second-order equation are determined using Equation (12) after removing last row and column in the matrix.

The standard error of estimation, S_τ/γ, is a measure of the mean derivation of data points from the third-order polynomial curve and can be determined as follows:

$$\frac{S_\tau}{\gamma} = \left(\frac{\sum\tau_i^2 - C_0\sum\tau_i - C_1\sum\gamma_i\tau_i - C_2\sum\gamma_i^2\tau_i - C_3\gamma_i^3\tau_i}{n-4}\right)^{\frac{1}{2}} \tag{13}$$

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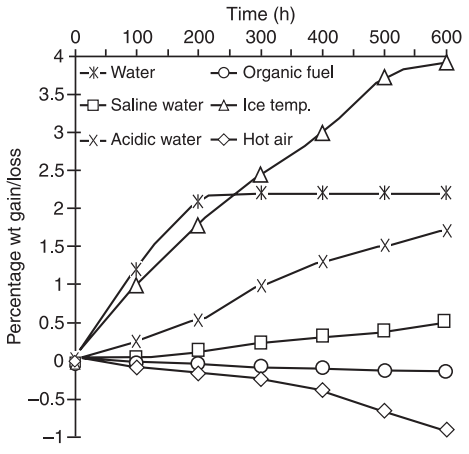

Figure 3: Percentage of weight gain/loss of bi-directional carbon/epoxy composite at different duration of exposure in different environmental conditions

and second-order curve,

$$\frac{S_\tau}{\gamma} = \left(\frac{\sum \tau_i^2 - C_0 \sum \tau_i - C_1 \sum \gamma_i \tau_i - C_2 \sum \gamma_i^2 \tau_i}{n-3}\right)^{\frac{1}{2}} \quad (14)$$

Results and Discussion

The results have been presented in two groups, i.e. the results for the virgin specimens and the results for the environmentally effected specimens. The effect of environment has been presented in the form of weight gain/loss in Figure 3. The shear stress–strain values of CFRC specimens with different environmental conditions and with different duration of exposure are shown in Figure 4, and in Figure 5, the percentage degradation of ultimate shear strength under different environments are shown. The shear modulus values obtained after environmental exposure have been compared with virgin shear modulus and shown in Figure 6 with the different durations of exposure.

The above observations can be analysed in the following context.

1 Effect of rail-shear test on virgin specimens,
2 Effect of moisture on shear strength,
3 Effect of temperature on shear strength, and
4 Effect of environment on shear modulus.

Effect of rail-shear test on virgin specimens

The results of the rail-shear test has been analysed under (i) preliminary test results, and (ii) effect of rail configuration.

Preliminary test results

The rail-shear specimens are designed with larger aspect ratio, i.e. b/a = 10. A large specimen information is randomly introduced by Whitney [12], which demonstrated that the orthotropic rail-shear

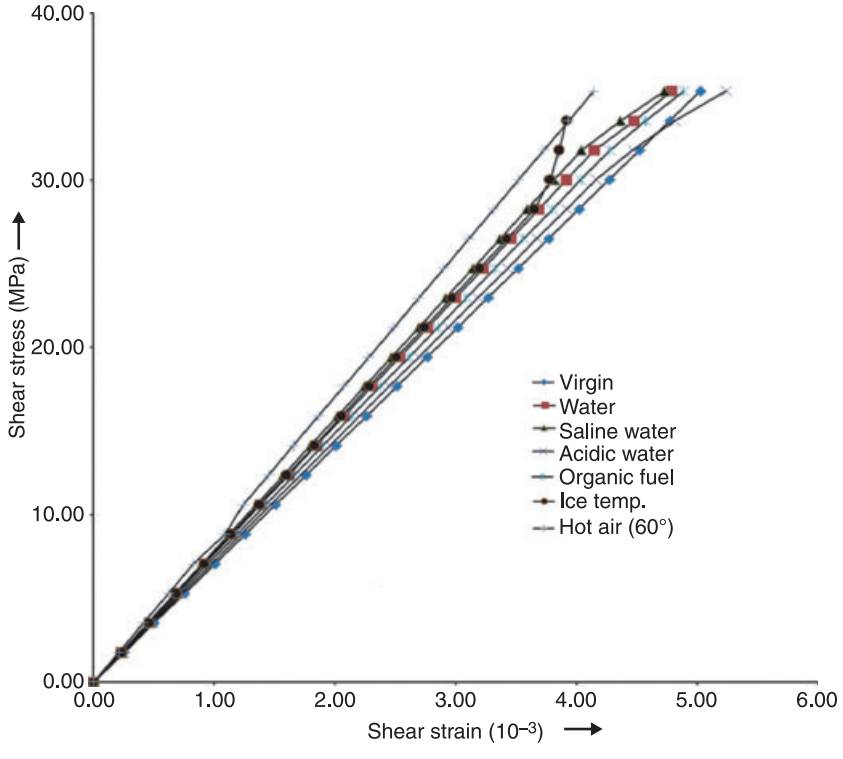

Figure 4: Shear stress–strain diagram of Bi-directional carbon/epoxy composite after 500 h. Exposure in different environmental conditions

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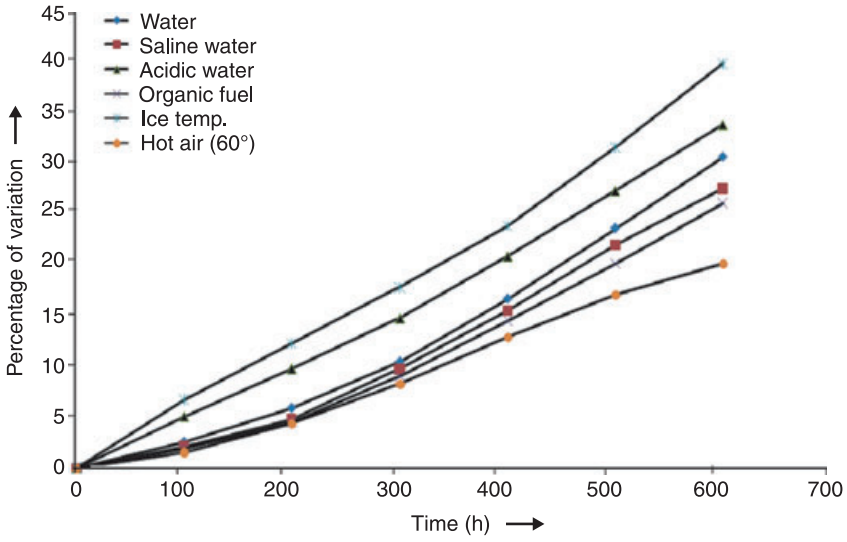

Figure 5: Percentage of shear strength variation after different duration of environmental exposure priory (w.r.t. virgin strength)

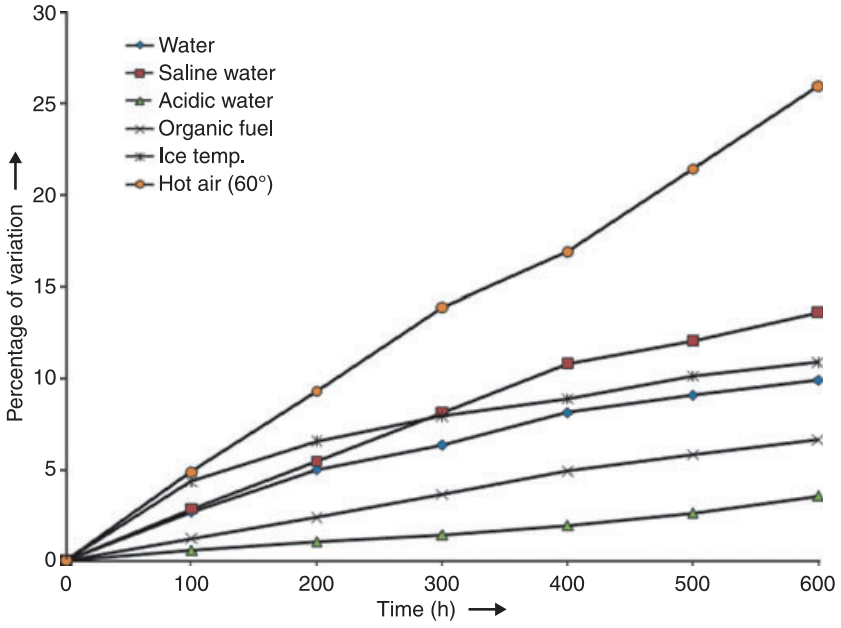

Figure 6: Pecent shear modulus variation after different duration of environmental exposure priority (w.r.t Virgin modulus)

specimens with b/a ≥ 10 exhibit a uniform shear state across the centre of the specimen. Preliminary tests have been conducted to identify any problem associated with bolting of the test specimen to the rails. The standard procedure for testing bolted-rail shear specimens is to use a fine grit emery paper placed between the rail and test material to provide a sufficient friction force when clamped, so that slippage does not occur.

The room temperature shear strength data and shear tangent modulus data of the bi-directional laminates obtained by using the bolted, uniform rail configuration provided an average ultimate shear stress of 49.51 MPa, which is an order of 8.5% of the ultimate tensile strength. The shear modulus is in the range of 7.03 GPa, which is approximately one-fifth of the tensile modulus of the material.

Effects of rail configuration

The shear strength in the principal material directions is independent of differences in tensile and compressive behaviour and it must be a pure shear stress by definition. The shear behaviour is quite nonlinear to fracture. Thus, it was of interest to conduct tests to examine the test method as well as to examine the shear response of the material. In-plane normal strain, ϵ_x and ϵ_y, at the centre of the specimen has been examined for the configuration. After 70% of total loading, the specimen behaved in a nonlinear manner. This is an indication of load redistri-

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bution occurring within the bolted, uniform-rail specimen and is attributed to localised slippage. Thus, it appeared that the attachment methods are more refined and will eliminate load redistribution within the test material to obtain an acceptable stress–strain data through the rail-shear test.

For lower loads, the normal in-plane strains at the centre of the specimen for the uniform rail configuration are much less. In the determination of ultimate shear strength, the use of uniform rails produces more acceptable stresses in the specimen test section than the other methods of testing. The room temperature shear stress–strain data of the bi-directional carbon/epoxy laminates, which are bolted uniformly to rail specimens, have provided an adequate measure of initial shear modulus. The average value of ultimate shear strength measured for these laminates is again conservative because of load redistribution which may be the result of localised slippage. The experimentally determined effect of the rail shear configuration on the stress–strain behaviour of the laminates is almost equal for all the tested specimens as anticipated.

Effect of moisture on shear strength

The bi-directional carbon/epoxy specimen's shear strength was measured after being preconditioned in four different types of liquid, i.e., water, saline water, acidic water, and organic fuel for different selected durations as mentioned earlier. The percentage of liquid penetration into the material was calculated using Equation 4. The weight gain or loss data are shown in Figure (3).

The effect of liquid depends on the type of matrix used in the composite, type of fibre, interfacial bonding of the fibre and matrix and presence of voids or discontinuities on test specimens. Using an ASTM standard, the calculated void percentage in the present material averages 0.1%. The liquid particles diffuse into the material and cause the void filling. Gradual expansion of the test specimens occur by swelling the boundary of the void because of osmotic pressure of the liquid. So, in the process, more liquid penetrate into the material and cause the decrease in interfacial bond strength. So, there is the loss of strength and stiffness.

The influence of liquid has caused the following effects on material contiguity:

(a) Loss of strength of the reinforcing fibres by a stress corrosion mechanism,

(b) Degradation of the fibre-matrix interface resulting in loss of adhesion and interfacial bond strength,

(c) Permeability of the matrix material to corrosive agents such as water or other liquid which effects both 'a' and 'b',

(d) Normal viscoelastic dependence of matrix modulus and strength on time and temperature,

(e) Combined action of temperature and moisture-accelerated degradation, and

(f) Effect on glass-transition temperature of the polymeric matrix.

It has been observed that the properties like corrosiveness of the liquid and density of the liquid have significant influence on the diffusion rate of the liquid percentage into the material. It also depends on the chemical activation of the medium with the constituent ingredients. The percentage of liquid absorption after accelerated exposure for different durations are shown in Figure 3 and obtained experimental data for shear strength and shear modulus are listed in Tables 2 and 4 respectively.

The percentage of shear strength degradation because of liquid environment reaction is shown in Figure 5. It has been observed that the percentage of degradation in shear strength is highest in acidic water and lowest in organic fuel. With respect to the rate of liquid absorption in different durations of exposure, the degradation of strength value is also accelerated for each case as the amount of liquid interacts with the fibre-matrix interface. As a consequence, weakening of the bond strength of fibre and matrix occurred. It depends on the amount of liquid that penetrates into the matrix material. The rate of degradation is maintained almost in equal percentage for each type of liquid exposed specimens as the durations of exposure increase. But, similar variation is absent in case of water-exposed specimens because of less corrosive nature.

Effect of temperature

Effect of temperature is another antique on present study of environmental effects. Observations were also carried out for the effects of low- and high-temperature environments on shear properties of bi-directional woven CFRC after exposing them for different durations. The selected temperatures are ice temperature (0 °C) and hot air (60 °C). Except to these temperature testing, the room temperature (27 ± 2 °C) testing was carried out. The measured shear strength under those environments is shown in Table 3. The percentage variation of shear strength for environmentally effected specimens with respect to virgin strength (room temperature testing results) was determined and shown in Figure 5.

A sizeable amount of degradation of material strength has been found for low temperature treated specimens, and a large value of weight gain has been measured in the same environment. But there

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was a minimum amount of weight loss in hot air and less reduction in shear strength values in comparison to low temperature as shown in Figures 3 and 5. The temperature effect on in-plane shear strength can be analysed on the line of thermal conductivity of the different constituents in CFRP composite.

The material has two constituents, i.e. one is fibre and the other one is polymeric matrix. Both of the constituent materials have dissimilar physical properties, like different coefficient of thermal expansion. Fibre and matrix have dissimilar thermal expansion characteristics. So, it caused the dissimilar shrinkage in low temperature and unlike expansion in high temperature. When the duration of environmental exposure was increased, thermal character was further influenced by time rate of weight gain or weight loss. At low temperature, the thermosetting polymeric matrix behaves like a brittle material, and at high temperature, a small amount of rigidity increases on the material. Thus, the temperature significantly influenced the interface strength and interface bonding, and there may be detachment of fibres at the juncture of the fibre-matrix bonding and may cause microbuckling of the fibre. Development of microcracks in the interface region is another consequence of the temperature influence. It causes the degradation of in-plane shear strength up to a sizeable margin. The process of strength degradation continued as the duration of exposure in the similar temperature environments increased. The shear property also changed proportionately.

Studied results have shown that there is almost uniform rate of decrease in the strength value at high temperature as well as in low-temperature conditions when compared with room temperature results. But percentage of strength reduction is more severe in the case of low temperature with respect to high temperature. This may be attributed to the influence of low temperature, which has caused the carbon/epoxy material to behave like a brittle material.

Effect of environments on shear modulus

The shear stress–strain data of bi-directional carbon/epoxy composite is shown in Figure 4 after various environmental exposures. The shear modulus calculated from the shear stress–strain diagram after different durations of environmental exposure is presented in Table 3, and percentage of variations in shear modulus obtained for environmentally exposed specimens with respect to shear modulus of unexposed specimens are shown in Figure 6.

The apparent cause of modulus value change under different environmental conditions may be attributed to the following effects.

1 The penetration of liquid into the fibre-matrix interface weakened the bond strength by swelling effect.
2 Chemical reaction or corrosion with fibre and matrix caused the stiffness reduction.
3 Effect of low temperature on physio-thermal properties of fibre and matrix caused the fibres or matrix, or both, to behave like a brittle material.
4 Expansion and contraction properties mismatch in fibre and matrix materials.
5 Combined action of temperature and environmental moisture affected the visco-elastic property of the fibre and matrix material, like the change in glass-transition temperature (T_g) value.
6 Change of hardness of epoxy at high temperature.

Basically, the modulus of the material is related to rate of change of shear strain per rate of shear stress. If the material exhibits high strain at low stress, then the modulus will be less as in ductile material and if the material exhibits lower strain at higher stress then the modulus will be higher as in composite materials. But the comparative shear stress–strain diagram (Figure 4) shows that the strain rate decreases as the composite is exposed to different environments for different durations. In carbon fibre reinforced composites, the expected influence of environments is the highest on the polymeric matrix in comparison to fibre. Instead of possessing ductility in loading, it was less ductile than expected, as there was an accelerated degradation of matrix properties in the environment, and the environmental exposure under various environmental conditions caused the ageing effect on the material. Therefore, there is a significant change in shear modulus. Again, shrinkage, swelling and expansion have detached the fibre-matrix bonding and developed microcracks at the juncture of fibre-matrix attachment. In some cases, the environment has caused the microbuckling of fibres. Overall, there is less amount of straining at higher load, and results in high modulus.

Conclusions

The following conclusions have been drawn from the experimental studies of shear modulus and shear strength of bi-directional carbon/epoxy composite by 'rail-shear' test method after adverse environmental influence for several duration periods:

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1 A major influence of environments on the specimen is the non-uniformity in stress distributions, and the type of environment.
2 Liquid environments have shown a significant amount of liquid penetration which depends on the material's diffusion constant, type of liquid (either corrosive or non-corrosive), and density of the liquid medium.
3 Although a significant amount of liquid penetration was recorded in water medium compared to acidic water, the corrosiveness of acidic water reduced the material shear strength extensively with respect to water.
4 It has been observed that acidic water has caused corrosion effect over matrix material and reduced the shear strength. So, it proves the contribution of matrix in integrity of composite structure.
5 Organic fuel and saline water were two other corrosive liquids used as environment. But, those mediums have no significant influence in shear strength degradation when compared to the other two liquids tested (saline water and acidic water).
6 The temperatures have also played a significant role in the shear properties of composite material because of the presence of dissimilar constituents. In low temperature (ice), the highest shear strength degradation occurred. At high temperature (hot air of 60 °C), the lowest shear strength degradation was noted.
7 The shear modulus values obtained in different environmental conditions also differed as per the environmental hostility. It is in higher range for hot air of 60 °C in comparison to all other environmental conditioning and even in comparison to virgin test results. The cause may be attributed to lower rate of straining at applied load and this is because of brittle behaviour of matrix material.

Thus, shear properties of bi-directional carbon/epoxy composite by rail-shear test method under the influence of various environmental conditions and with different duration of environmental ageing have contributed significant design data and may be accepted as design properties for future application where this bi-directional carbon/epoxy composite have the use.

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